A STUDY OF EFFECTS OF HIGH ENERGY ELECTRON RADIATION ON SELECTED ELECTRONIC DEVICES

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THESIS

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ON
SELECTED ELECTRONIC DEVICES

by

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A Study of Effects of High Energy

Electron Radiation

on

Selected Electronic Devices

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Lieutenant, United States Navy
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ABSTRACT

This study investigates the behavior of TTL NAND Gates (Signetics SE480Q) and MOS Field Effect Transistors (2N4067) in an electron radiation environment (produced by the Naval Postgraduate School Linear Accelerator).

The electron radiation within two planetary radii of Jupiter is estimated to be of the order of 5 X 10^7 electrons per square centimeter per second. The "Grand Tour" outer planets space probe was to spend about ten hours in this environment thus receiving an exposure of about 2 X 10^{12} e^-/cm^2.

Exposures of about 10^{15} e^-/cm^2 for TTL NAND Gates and 10^{14} e^-/cm^2 for the MOSFETS were required before failure or serious degradation of performance occured. Therefore, in the electron environment near Jupiter, satisfactory operation should be expected for about 500 hours for the MOSFETS and 5000 hours for the TTL NAND Gates.

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ACKNOWLEDGEMENTS

The author wishes to extend particular appreciation to the following individuals for their time and assistance in preparation of this study:

Professor John N. Dyer and Associate Professor Edgar B. Dally, my thesis advisors.

Assistant Professor X. K. Maruyama for his assistance in setup and operation of the experiments.

Assistant Professors C. C. Wang and T. F. Tao for their aid in determining methods of measurements.

My wife, Rose, for her patience and encouragement.

I. INTRODUCTION

At the onset of this study it was envisioned that a "Grand Tour" space probe would be launched in the near future to probe the vicinities of the outer planets. During the life of the probe, the largest amount of radiation it was expected to encounter was in the vicinity of Jupiter. Although the "Grand Tour" has since been cancelled, this study is still pertinent to space vehicles making direct probes of Jupiter. Estimates show that Jupiter is surrounded by a belt of high energy (20-30 MeV) electrons extending about one planetary diameter into space as shown in Figure 1. [1]

Low energy electron investigation was done by NASA, Goddard Space Flight Center, Greenbelt, Maryland using 1.5 MeV electrons. [2&3] Jet Propulsion Laboratory, Pasadena requested that the Naval Postgraduate School linear accelerator be used to extend the study to higher energy electrons. The results of Refs. 2&3 are not included herein.

A number of TTL NAND gates (Signetics SE480Q) and MOS field effect transistors (2N4067) were provided by JPL. The TTL NAND gates were the same as reported in Ref. 2 but the MOSFETS were not the same type as reported in Ref. 3 but were similar. The devices were exposed to 16-85 MeV electrons and the results reported to JPL. [4&5]

II. DESCRIPTION OF THE NPS LINAC

The Naval Postgraduate School linear accelerator (LINAC) is a pulsed machine which delivers 60 pulses per second, each pulse of about one microsecond duration. The electron energy can be selected anywhere in the range from about 16 MeV to 100 MeV. Lower energies are possible but the beam transport system becomes unreliable at lower energies, and consequently the method of dosimetry (See section III) becomes unreliable.

For these experiments the LINAC was tuned to deliver about 5×10^{10} electrons per pulse, or 3×10^{12} electrons per second. The flux incident on the circuit was calculated from the spatial profile of the beam and the total number of electrons delivered, as described in Section III.

The accelerator consists of three ten-foot accelerating sections separated by short drift spaces which contain steering coils. The collimator at the exit of the third accelerator section provides the image for the beam deflecting magnets and quadrupole lenses which follow. The beam is brought to a focus at the center of a "target chamber" (which was empty for these experiments) and then diverges slightly, passes through a 5 mil aluminum window, and then passes through several inches of air to the point where the circuits were exposed. The electrons pass through the circuit and are collected by a Faraday Cup. The measurements of the number of electrons delivered by the machine

are done by the Faraday cup or the Secondary Emission Monitor inside the target chamber. Sketches of the exposure locations are shown in Figures 2 & 3. This location is approximately 60 feet from the accelerator control room where measurements were actually made. The circuit under test was connected to test equipment and power supplies in the control room by RG/58 triaxial cable which was further shielded by a metal conduit to prevent RF interference from the LINAC. For some of the tests made, the cables imposed too much capacity; for these tests equipment was located in the exposure area and viewed by closed circuit television.

III. EXPOSURE METHODS AND CALCULATION OF THE FLUX

A. EXPOSURE METHODS

1. TTL NAND Gates

The exposure arrangement is shown in Figure 2. The circuit to be exposed was mounted in a flatpack holder and plugged into a connector box which provided 14 BNC connectors to accomodate the triaxial cables running to the control room. The flatpack holder was modified so that no material was in the path of the beam before it struck the circuit. A ZnS coated mylar screen was mounted as shown in front of the circuit, with a small hole (about 1/8" diameter) centered at the active part of the circuit. The screen was observed by TV in the control room and provided a visual indication that the electron beam was correctly steered;

when the beam was incident on the hole in the screen an illuminated "halo" was seen around the hole. (The spatial extent of the beam was greater than the size of the hole.) A Cinemoid #48 film was mounted behind the circuit as shown; this film changes optical density when exposed to radiation and thus provides another check on the centering and size of the beam.

To position a circuit correctly before an exposure was started, a "dummy circuit (one sacrificed for this purpose) was mounted and the beam was steered until it was incident on the hole in the ZnS screen. The dummy was then removed and the test circuit put in its place. The positioning was then rechecked by exposing the circuit to one or two single machine pulses at reduced flux. It is felt that the amount of initial radiation given to the circuit in this way (about 10^{10} e^-/cm^2) is negligible.

2. MOSFETS

The exposure arrangement is shown in Figure 3. The transistor to be exposed was mounted in a holder which permitted the electron beam to strike the transistor unimpeded. Leads extending to the rear of the holder were separated as far as possible to reduce capacity. The leads then were connected to three BNC connectors so that coaxial cables could be used to further reduce capacity. A ZnS screen was placed around the holder to aid in centering the beam. Once the beam was correctly aligned, it was turned off, the holder with the transistor was placed in position and the beam turned on correctly positioned.

For characteristic curves, a Tektronix Type 576 curve tracer was used in the control station. (The long cable run had negligible effect on the results.)

For capacitance measurements a device was constructed as detailed in Appendix B. The long cable runs had an adverse effect on measurements necessitating placing all equipment except power supplies and the XY recorder in the exposure area.

B. CALCULATION OF FLUX

The total number of electrons delivered by the LINAC was measured either by a calibrated SEM in the target chamber or by the charge accumulated in the Faraday cup, which is assumed to be 100% efficient for electron energies considered here. The accumulated charge was measured by a vibrating reed electrometer located in the control room. However, to determine the fluence which actually passed through the circuit, the cross-sectional profile of the beam had to be determined since not every electron collected by the cup had passed through the circuit.

Cinemoid #48 films were placed at the exposure location (with no circuit or holder present) and a number of exposures were made at different electron energies and fluences. The data obtained and the profiles determined from these data are shown in Figure 4 for beam energies of 28 MeV and 85 MeV. The dashed lines of this graph show the measured optical densities and the solid lines show the actual exposure profiles after corrections for nonlinearity in the response

of the film and the photodensitometer used for the measurements. Note that at the lower energy the beam was considerably more "blown up" by scattering through the 5 mil aluminum window. The difference was actually more striking than appears from Figure 4 since the exposures at low energy were three times as long as those at high energy.

To calculate the fluence at the circuit, which was located at the center of the beam profile, it was assumed that the profile was gaussian and symmetric around the beam center. [6]

Therefore

$$\phi(r) = \phi_o \exp \frac{-r^2}{2\sigma^2}$$

where $\phi(r)$ = fluence at radius r from beam center

ϕ_o = fluence at center of beam

The total number of electrons, N, delivered by the LINAC is then

$$N = \int_0^{\infty} r\,\phi(r)\,dr\,d\phi = 2\pi\sigma^2\phi_o$$

Hence $\phi_o = \dfrac{N}{2\pi\sigma^2}$

For σ use the values 1.4 mm and 3.4 mm taken from Figure 4 at 85 MeV and 28 MeV. N is measured from the charge on the Faraday cup. (At 28 MeV a further correction is required because the circuit and holder scatter some electrons away from the entrance to the Faraday cup.)

Inserting the values of σ into the last equation,

$$\phi_o = 8.1 \text{ N at } 85 \text{ MeV}$$

$$\phi_o = 1.4 \text{ N at } 28 \text{ MeV}$$

IV. TEST RESULTS

A. TTL NAND GATES

Each device contains 4 gates which are independent except for common V_{cc} and ground connections. Thus the gates in a single device can be connected and tested in different ways during a radiation exposure. Five different arrangements for individual gates were used as shown schematically in Figure 5. The results of tests performed on 14 devices (56 gates) follows.

1. V_{in} vs V_{out} Characteristics

For these tests the gates were connected as shown in Arrangement 1 of Figure 5. During exposure V_{in} was held at 0 volts and V_{cc} was held at 4.4 volts. The data were recorded as traces made on an XY recorder located in the control room. V_{in} was provided by a voltage supply also located in the control room. (Voltages at the circuit were found to be the same as those in the control room, that is, there were no appreciable ohmic losses in the connecting cables.) Tests were made in two ways: (1) the radiation was stopped and then the trace was made, and (2) the trace was made while the device was under radiation. No difference was noted.

Heating effects can easily disguise radiation effects. In the first exposure the devices were left in the beam with no attempt at maintaining constant temperature.

The result was an almost immediate shift in V_{in} vs V_{out} characteristics toward values expected at higher temperatures (estimated to be an increase of about 20° C) and recovery occured after radiation stopped. (The same result was obtained with a hot-air blower.) Therefore, for all the results reported here, the devices were maintained near room temperature by means of a cooling fan. It is not known if this simple cooling actually kept the devices from heating, but it is assumed that it did so because no obvious heating effects were observed when the fan was used and there were no changes in characteristics after radiation was stopped (which would indicate cooling).

Figure 6 is a copy of a typical recorder trace, representing the behavior of a device radiated with 28 MeV electrons. Devices radiated with 55 MeV and 85 MeV electrons showed the same general behavior. From these traces it appears that the most important change which occurs as a result of radiation is an increase in the low level (saturation) output voltage. Therefore the change in this voltage is plotted as a function of fluence in Figure 7. The points on this plot were obtained directly from the recorder traces and therefore are subject to large errors for small values of ΔV_o, which are barely readable from the traces. The important conclusion to be drawn from Figure 7 is that there is no apparent dependence upon the energy of the electrons used for the radiation.

2. V_{in} vs V_{out} with Pulsed Input

Four gates were connected as shown in Test Arrangement 2 of Figure 5. Two were exposed at 28 MeV and two at 85 MeV. The data were obtained as oscilloscope traces which showed the drop in V_{out} when the input pulse arrived. Again, the effect of radiation was to prevent the gate from switching to the proper value of low level output, much as was observed with Test Arrangement 1. Only this qualitative statement may be made regarding this test. The oscilloscope photographs were not accurate enough to allow a plot of ΔV_o to be made from them, and for the low energy exposure there was a LINAC failure which made dosimetry very uncertain.

3. Measured Change in Saturation Voltage

For this test, 8 gates (2 devices) were connected as shown in Test Arrangement 3 of Figure 5. Exposures were made at 28 MeV and 85 MeV. The results are plotted as Figures 8 and 9. Examination of these plots shows that there is no apparent difference in the 28 MeV and 85 MeV results.

4. Flip-Flop Test

Pairs of gates in each of 4 devices were connected as shown in Test Arrangement 5 of Figure 5, so that a pair would operate as a flip-flop circuit. Input pulses as shown would switch the circuit from one state to another. The output of one gate was observed on an oscilloscope located

in the exposure area by remote TV. The input pulses were of 3 volt magnitude.

These were irradiated with electrons of 28, 55, and 85 MeV. In each case the behavior was similar; an abrupt failure of the device to change from one state to another after a certain fluence was reached. In all cases a slight recovery was noted after the critical fluence was reached. The devices would change state after a few minutes but the difference in levels was much reduced. A slight increase in fluence then produced permanent failure.

The fluences at which failure was observed are given below.

Device #	Electron Energy	Fluence at Failure
7	85 MeV	1.9×10^{15} e^-/cm^2
8	55	4.1×10^{15}
9	85	3.3×10^{15}
10	28	3.3×10^{15}

No attempt was made to regain the operation of these circuits by changing the size of the triggering pulses or their separation. No energy dependence was noted.

5. Fall Time Measurements

This test was included more or less as an idea which occurred at the last moment, when only a few unexposed gates remained. After some unsuccessful attempts to arrange to have an oscilloscope in the control room, Test Arrangement 4 of Figure 5 was arrived at, with the oscilloscope in the exposure area and viewed by remote TV. The behavior of 3

gates of one device was measured with this arrangement. Copies of the oscilloscope traces (all were the same) are shown as Figure 10. As can be seen, the fall time increased with fluence. The test was not accurate enough to permit very quantitative results, but it does appear that an increase in fall time occurs at least as soon as an increase in saturation voltage, and may be equally valuable as an early indicator of changes caused by radiation.

6. General Conclusions

The circuits tested are fairly resistant to damage from a space radiation environment. There does not seem to be any serious changes in the characteristics of these devices for fluences up to approximately 10^{15} e^-/cm^2, regardless of electron energy. The saturation voltage exceeded design specifications of 300 mv at fluences of about 1.7×10^{15} e^-/cm^2, but some devices survived fluences of about 10^{16} e^-/cm^2, again regardless of electron energy.

B. MOSFETS

Various energies were used throughout the tests and again confirmed that the results were independent of energy.

Two parameters of these devices were measured; gate to source capacitance and characteristic curves. Each device consisted of two MOSFETS with a common source. Because of the common source and the method of measurement, capacitance of only one of the MOSFETS in each device could be measured. The characteristic curves of both MOSFETS in each device could be measured during each exposure. For comparison, a

number of 2N4360 transistors were similarly exposed and plotted. During one test, the device was allowed to set for 1.5 hours and showed no recovery.

1. Capacitance

The gate to source capacitance degraded with exposure as shown in Figure 11. The points on this plot were obtained from the XY recorder trace. A change of 1 pf (picofarad) was discernable but because of extraneous noise the values could not be read better than $\pm$ 1 pf.

2. Characteristic Curves

Photographs of the characteristic curves for the MOSFETS were taken at the control station when a significant change was noted. Transconductance was determined from these photographs. One of the MOSFETS in each device was continually tested during exposure while the other MOSFET was passive during exposure. The MOSFET that was passive invariably failed with exposures of less than 10^{13} e^-/cm^2. No attempt was made to plot the curves for these. The Transconductance of the "on" MOSFET is plotted in Figure 13. Once an "on" MOSFET had received an exposure of 10^{13} e^-/cm^2, if it were allowed to remain passive during the next exposure, it would immediately fail.

3. General Conclusions

Serious degradation of transconductance of these devices occured at exposures of less than 10^{13} e^-/cm^2 for devices which were passive during radiation. An order of magnitude improvement was obtained if the devices were in an active state during radiation.

Changes in capacitance were not as sensitive. Exposures of the order of 5×10^{15} e^-/cm^2 were required to cause significant changes in capacitance. Therefore capacitance changes are not a precursor of damage since transconductance changed significantly with exposures of the order of 10^{14} e^-/cm^2.

APPENDIX A

CONSIDERATIONS ABOUT ENERGY EFFECTS

Perhaps the most important conclusion that can be drawn regarding the behavior of these devices in a simulated space radiation environment is that there is no severe dependence upon the energy of the incident electrons. However, before generalizing this statement to conclude that energy effects should not be sought by further experiments, some theoretical aspects of the problem are discussed.

In Figure 15 the rate of energy loss by electrons in silicon is plotted as a function of their energy. Separate curves for ionization and radiation losses are shown. Note that the rate of loss by ionization is a slowly varying function of energy above about 1 MeV; (from 1.5 MeV cm^2/gm at 1.5 MeV to 1.9 MeV cm^2/gm at 100 MeV). Therefore, if radiation effects depend primarily on the ionization produced by the incident electrons, no appreciable energy effects would be expected. On the other hand, radiation losses increase rapidly with electron energy, being negligible compared to ionization losses at 1.0 MeV, equal to ionization losses at about 48 MeV (the critical energy for silicon), and dominant at higher energies. The question is: can the photons produced by this radiation be neglected as a source of radiation damage? The usual assumption is that they can be disregarded because their mean free paths are long compared

to the dimensions of a typical integrated circuit, and thus they escape without interaction.

The experimental results of this study seem to support the validity of this assumption. Examination of graphs shows that similar results occur regardless of the energy of the electrons. In Figure 12 there appears to be a discrepancy in this conclusion. However, if the dose rate on the circuits is noted it is apparent that there is an order of magnitude change in rate for the two sets of curves. It is felt that the rate of exposure is responsible for this discrepancy rather than the difference in energy.

APPENDIX B

CAPACITANCE MEASURING DEVICE

A device for measuring the gate to source capacitance of a MOSFET remotely and semi-automatically was constructed using Ref. 7 as a guide. A schematic of the device is shown in Figure 16. Numerous difficulties were encountered with the construction and testing of this device. The most critical part of this circuit is the selection of the Zener diodes. Reference 7 notes that these diodes should be matched within 1%. This is critical for the correct operation and linearity of the device. The circuit constructed for this study used diodes which were as closely matched as were obtainable at the time with shelf components but were not within the 1% range recommended. Consequently the output was nonlinear.

The most difficult problem encountered after construction of the device was the DC level of the output. The zero capacitance level of the output was approximately 1.5 volts and changes in capacitance of 20 pf caused the output to change by a few millivolts. This was unacceptable because the recording instruments could not be made sensitive enough to read a 1pf change with the relatively large DC level. Therefore an operational amplifier circuit was constructed to eliminate the 1.5 volts and to amplify the changes due to capacitance. Satisfactory results then followed but the

nonlinearity persisted. Because of this nonlinearity, calibration curves had to be plotted prior to each measurement.

Because the operational amplifier had a gain of 100, and the measurements were to be accurate to within 1 pf, fluctuations in power supply voltages were critical. This problem was removed by using batteries as the power supply. It is recommended that this device be reconstructed as described in Ref. 7. The schematic for the device as should be constructed is shown in Figure 17. Particular emphasis should be placed on matching the Zener diodes to 1%. The use of coaxial cable for the interior wiring is also recommended.

APPENDIX C

DRAWINGS AND GRAPHS

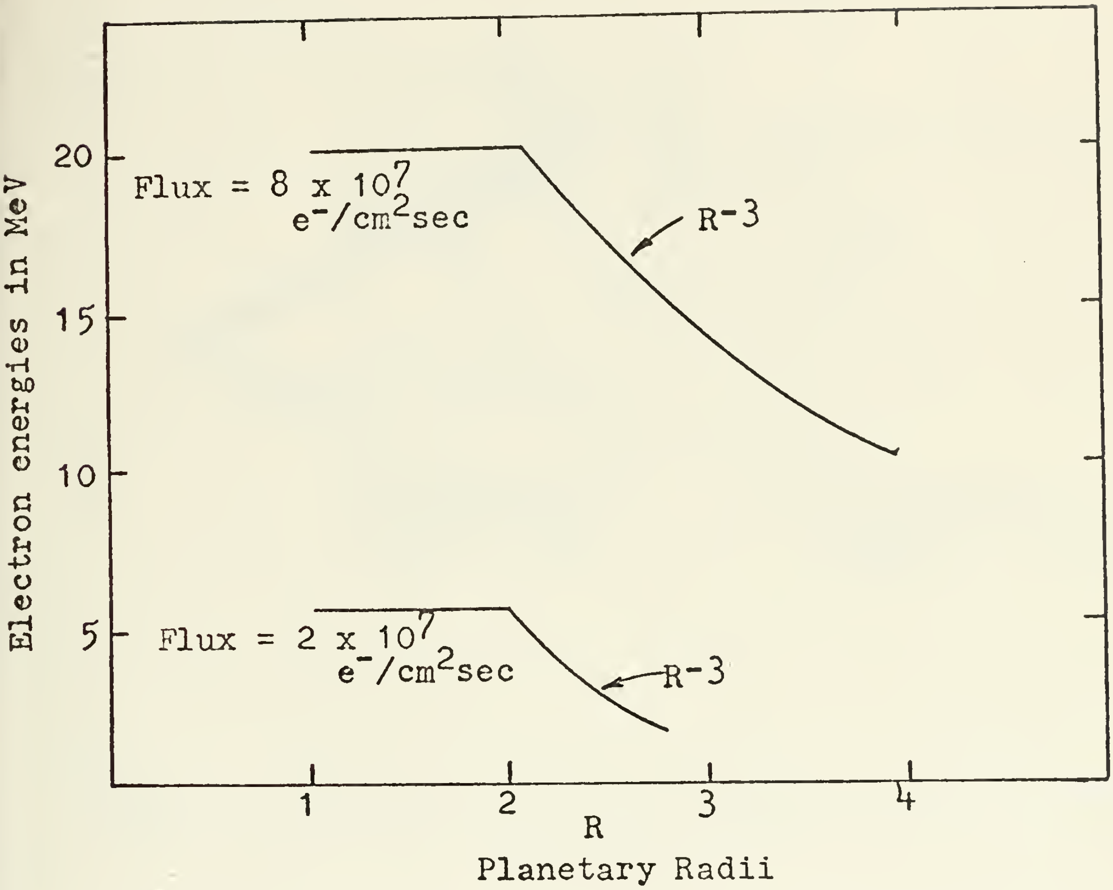


Figure 1. Estimated electron radiation environment in the vicinity of Jupiter

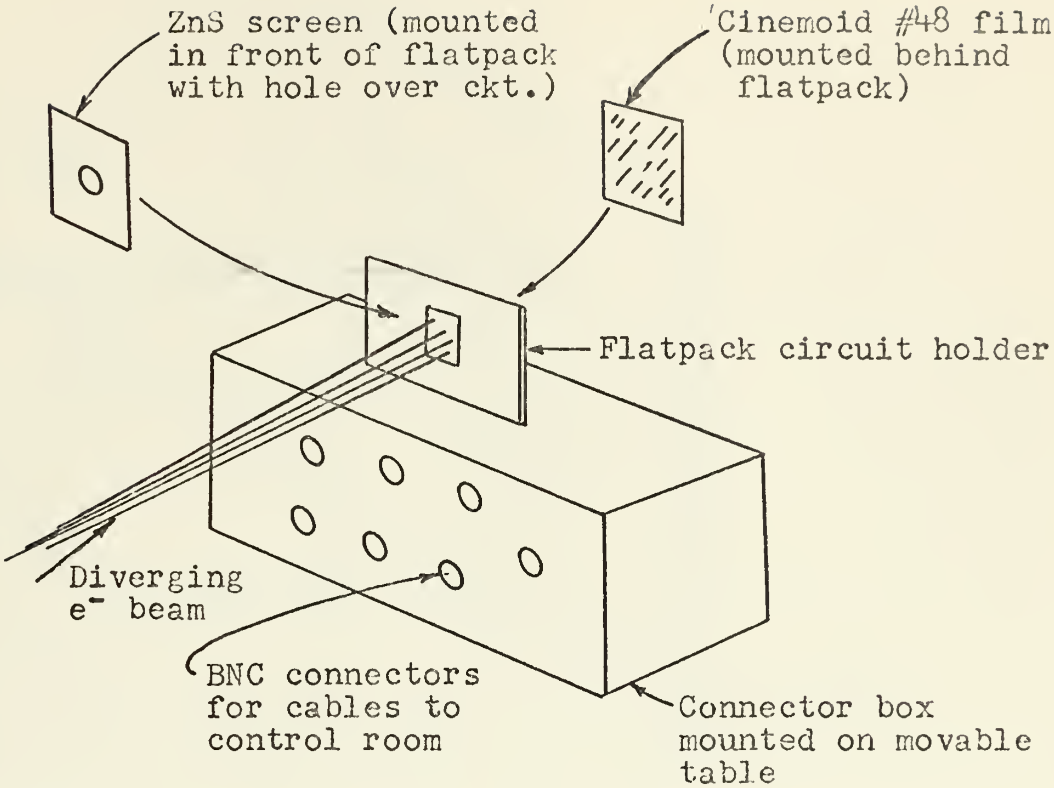


Figure 2. Sketch of exposure arrangement for TTL NAND gates

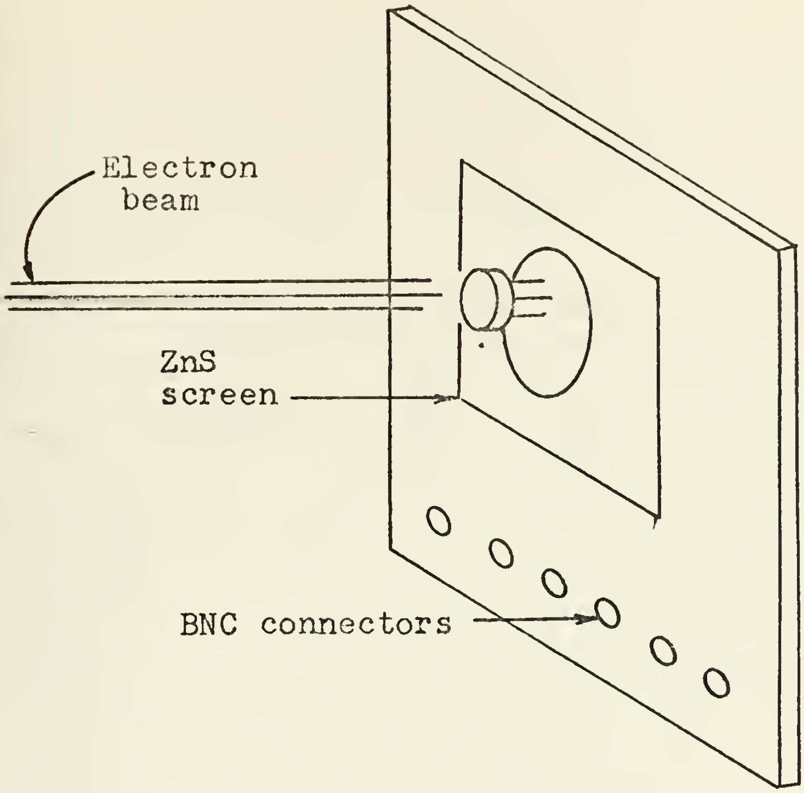


Figure 3. Sketch of exposure arrangement for MOSFETS

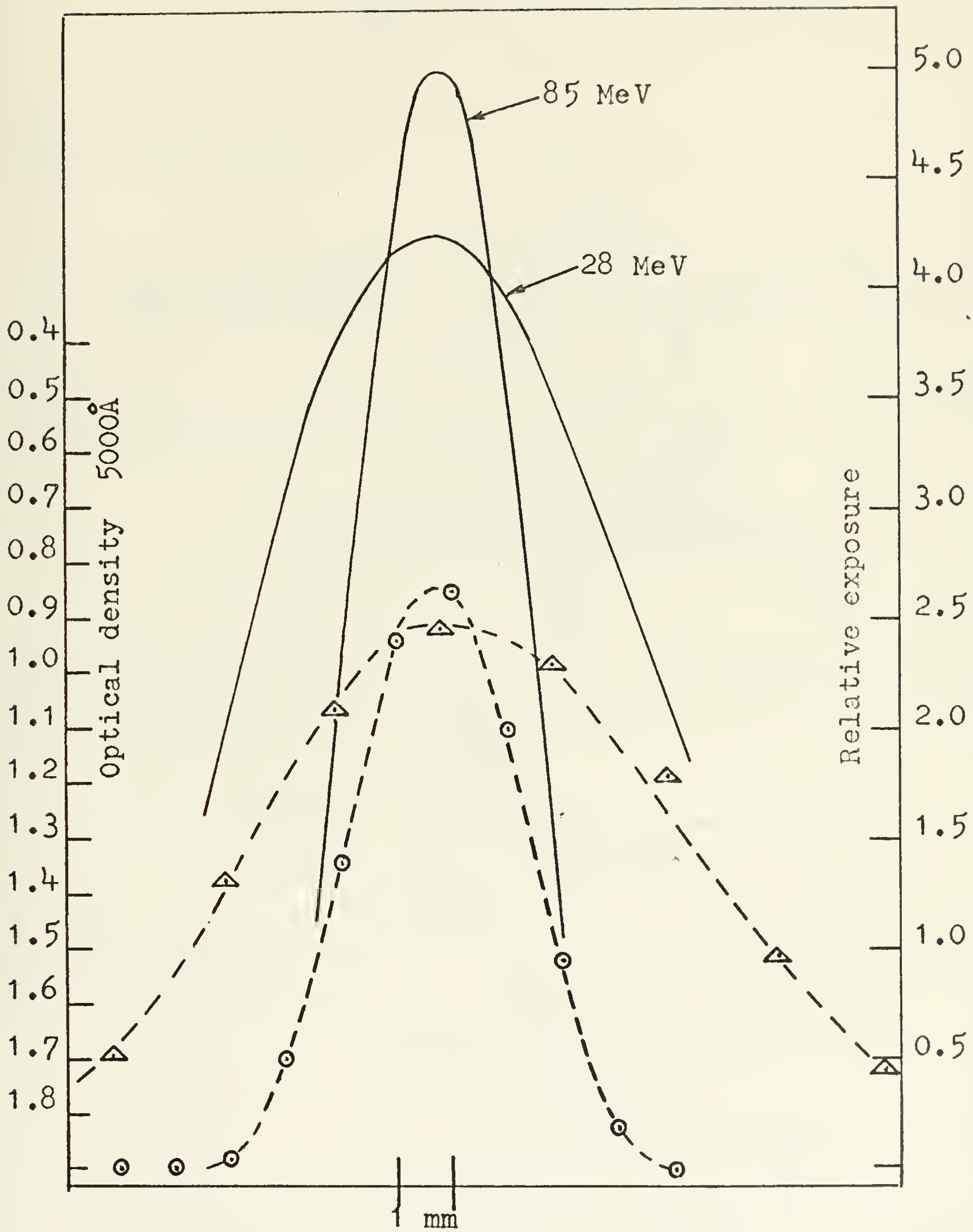


Figure 4. Beam Profiles

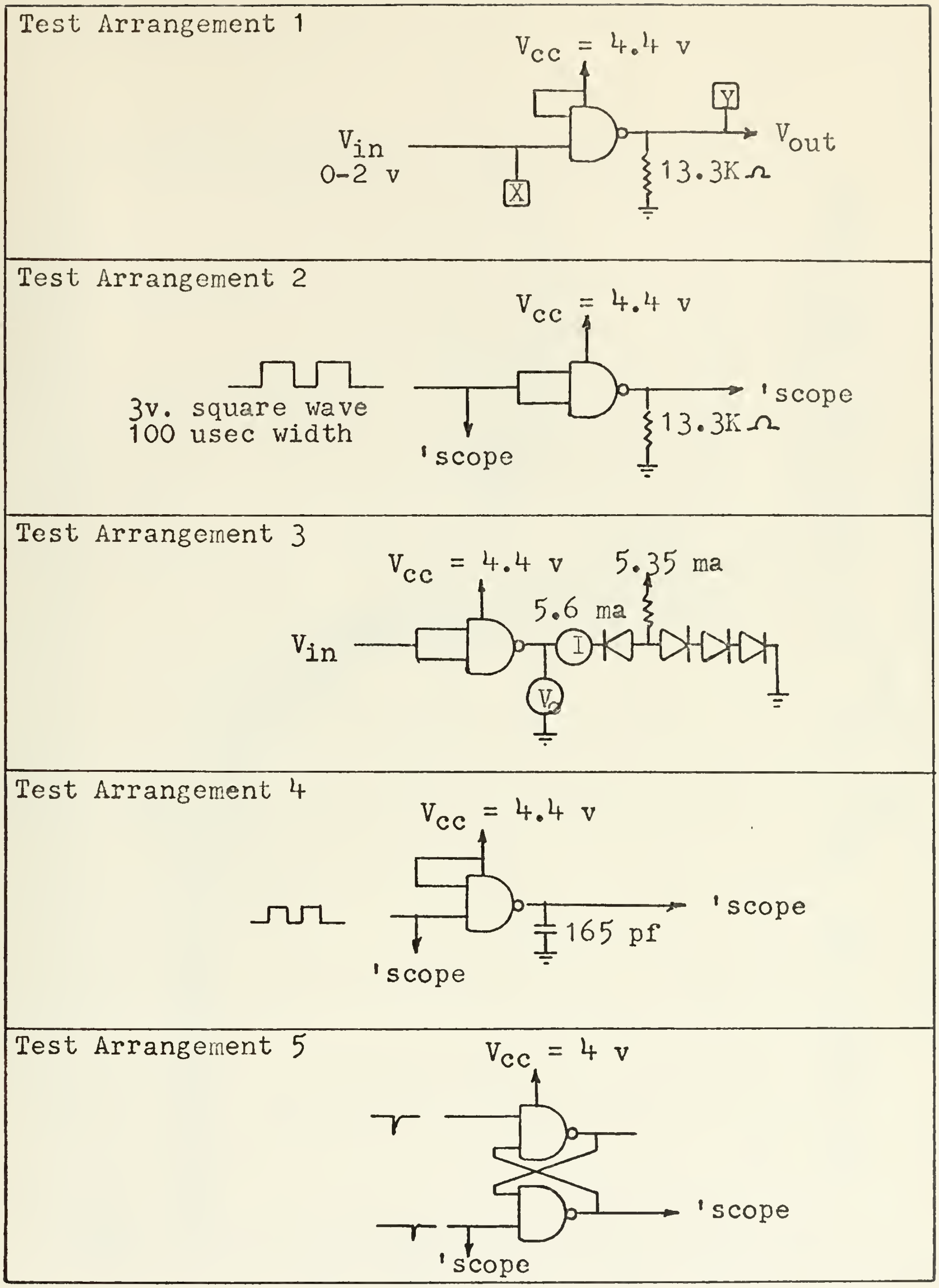


Figure 5. Test arrangements for TTL NAND gates

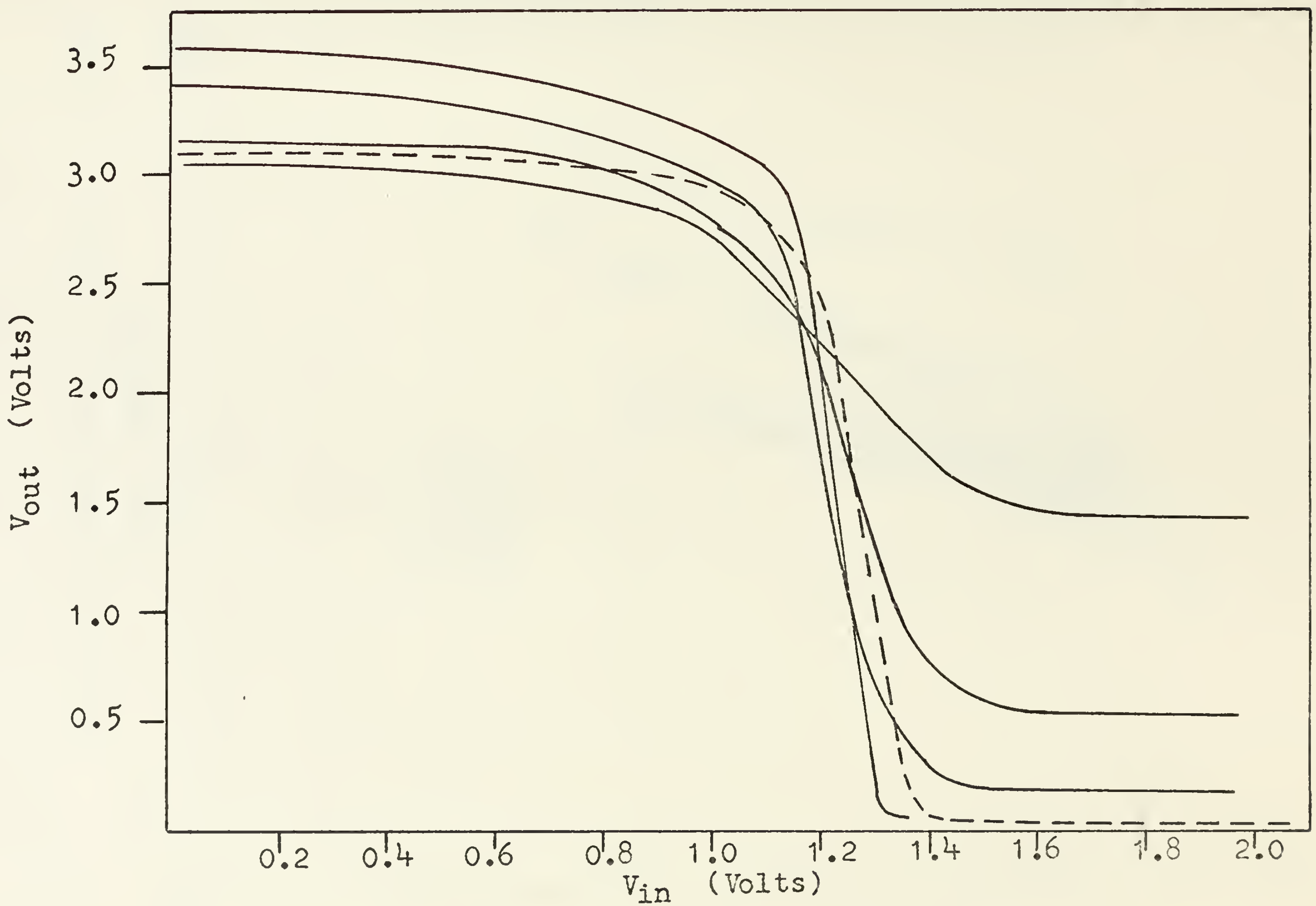


Figure 6. Typical XY recorder trace

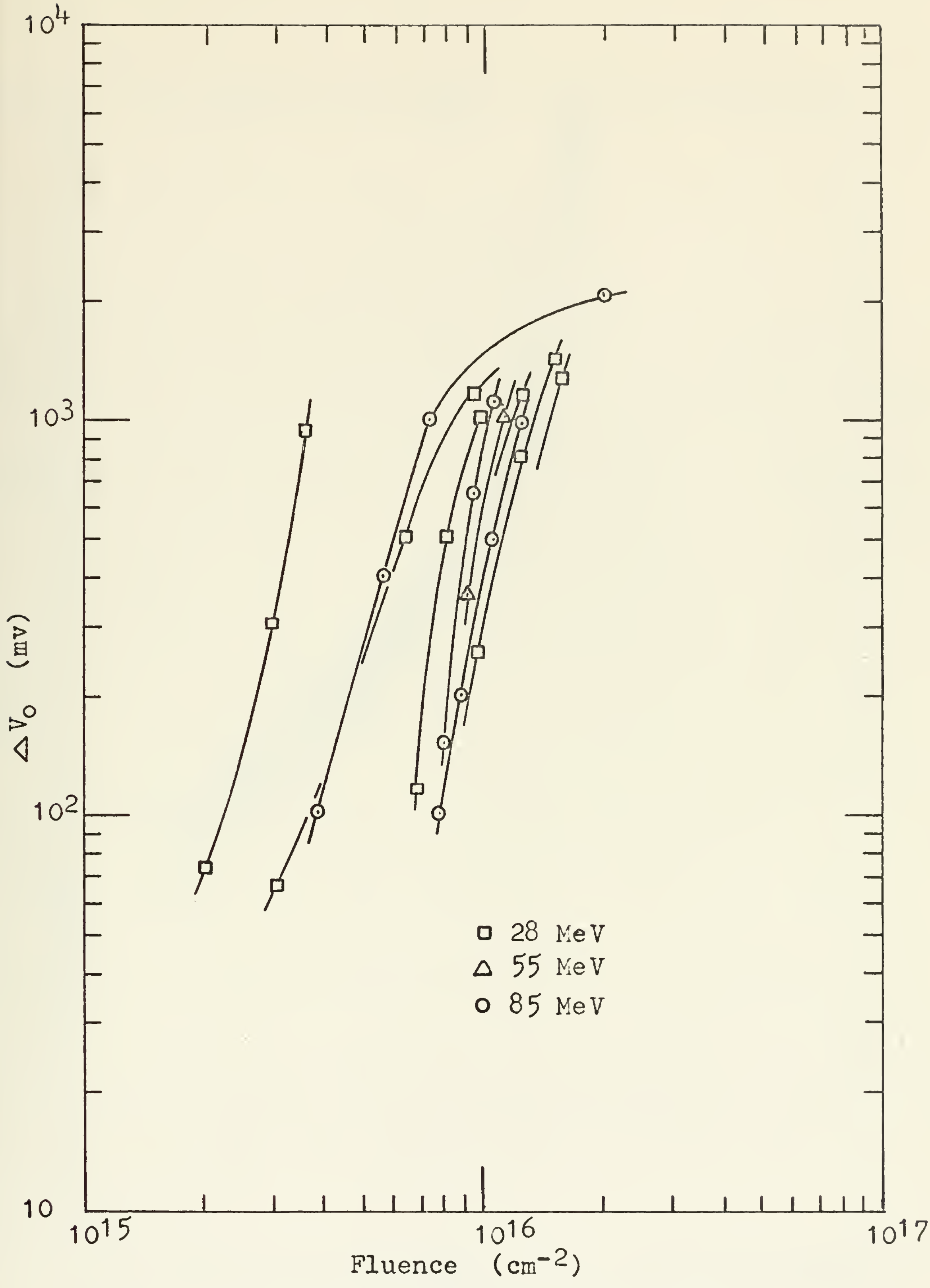


Figure 7. Change in low output vs fluence

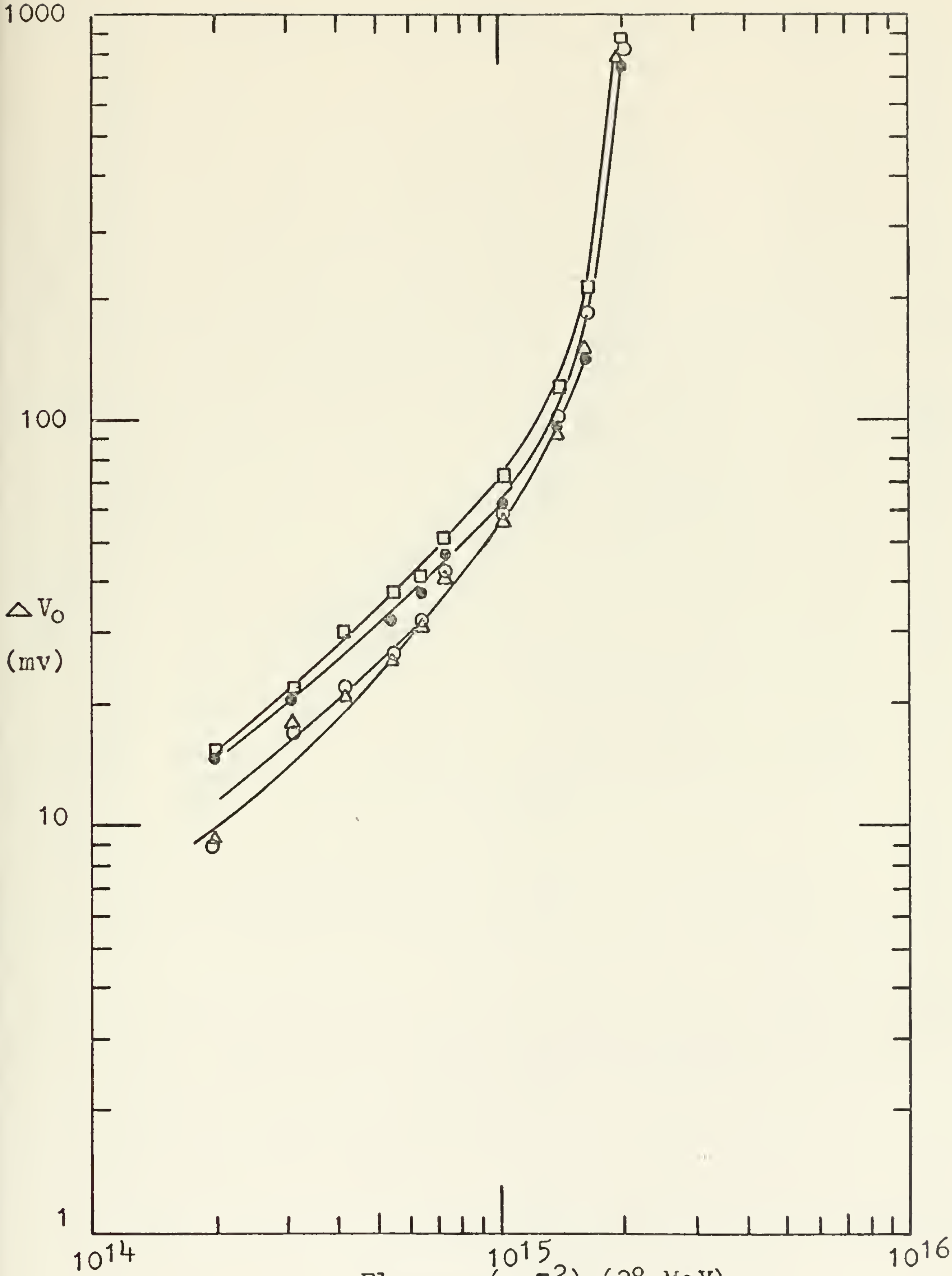


Figure 8. ΔV_o vs Fluence at 28 MeV

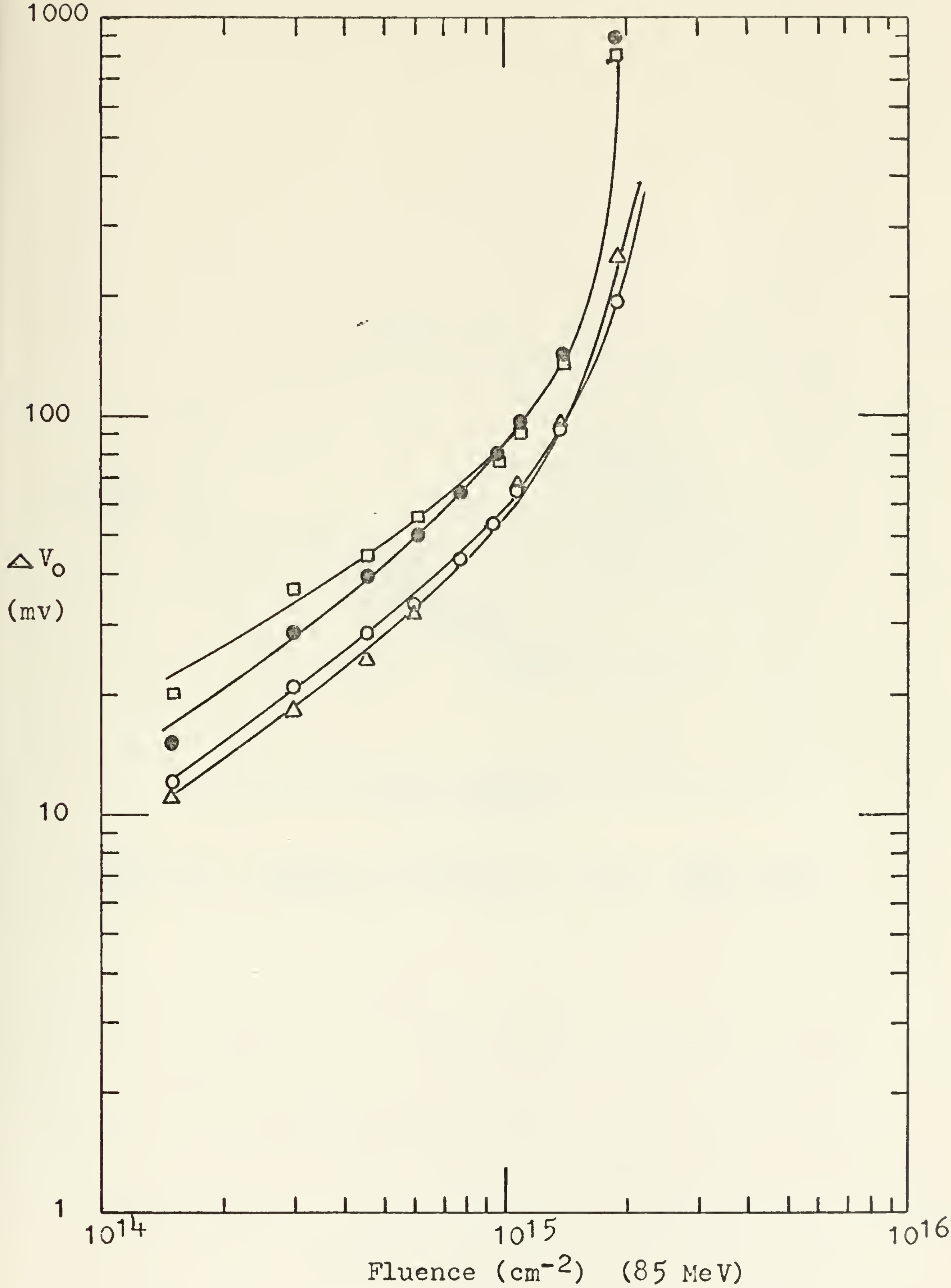


Figure 9. $\triangle V_o$ vs Fluence at 85 MeV

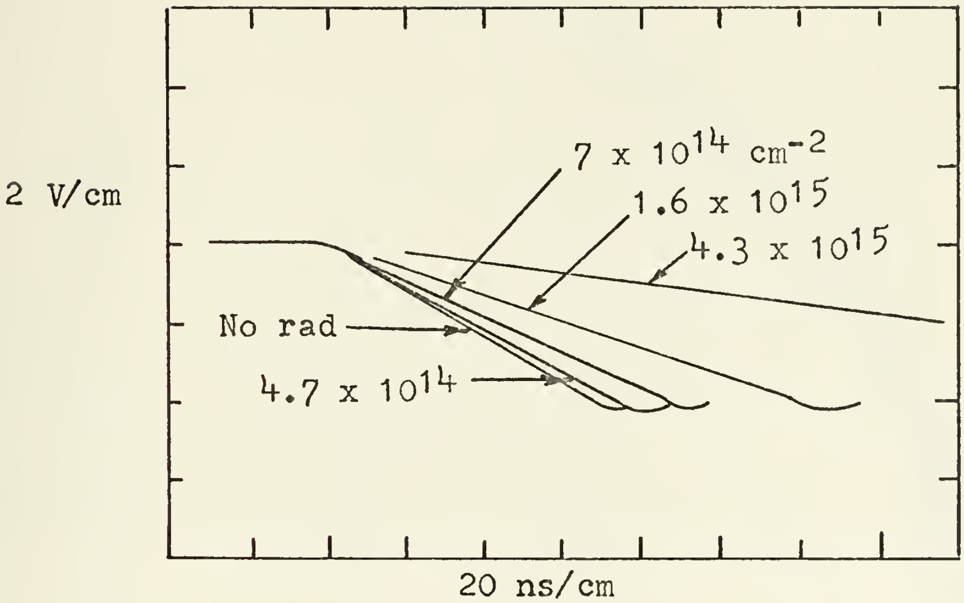


Figure 10. Sketch of results of Fall Time Test

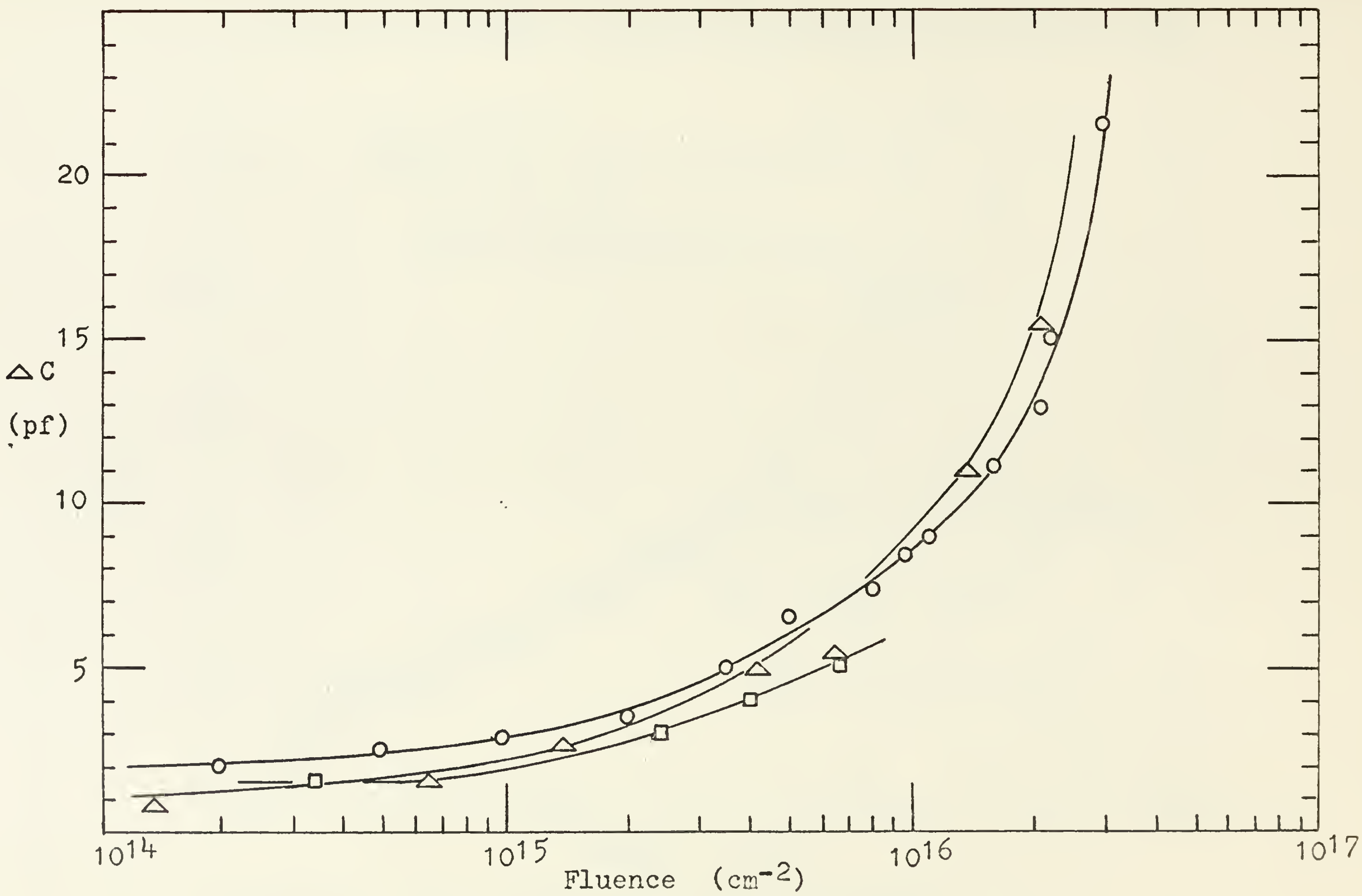


Figure 11. △C vs Fluence for 2N4067 MOSFETS

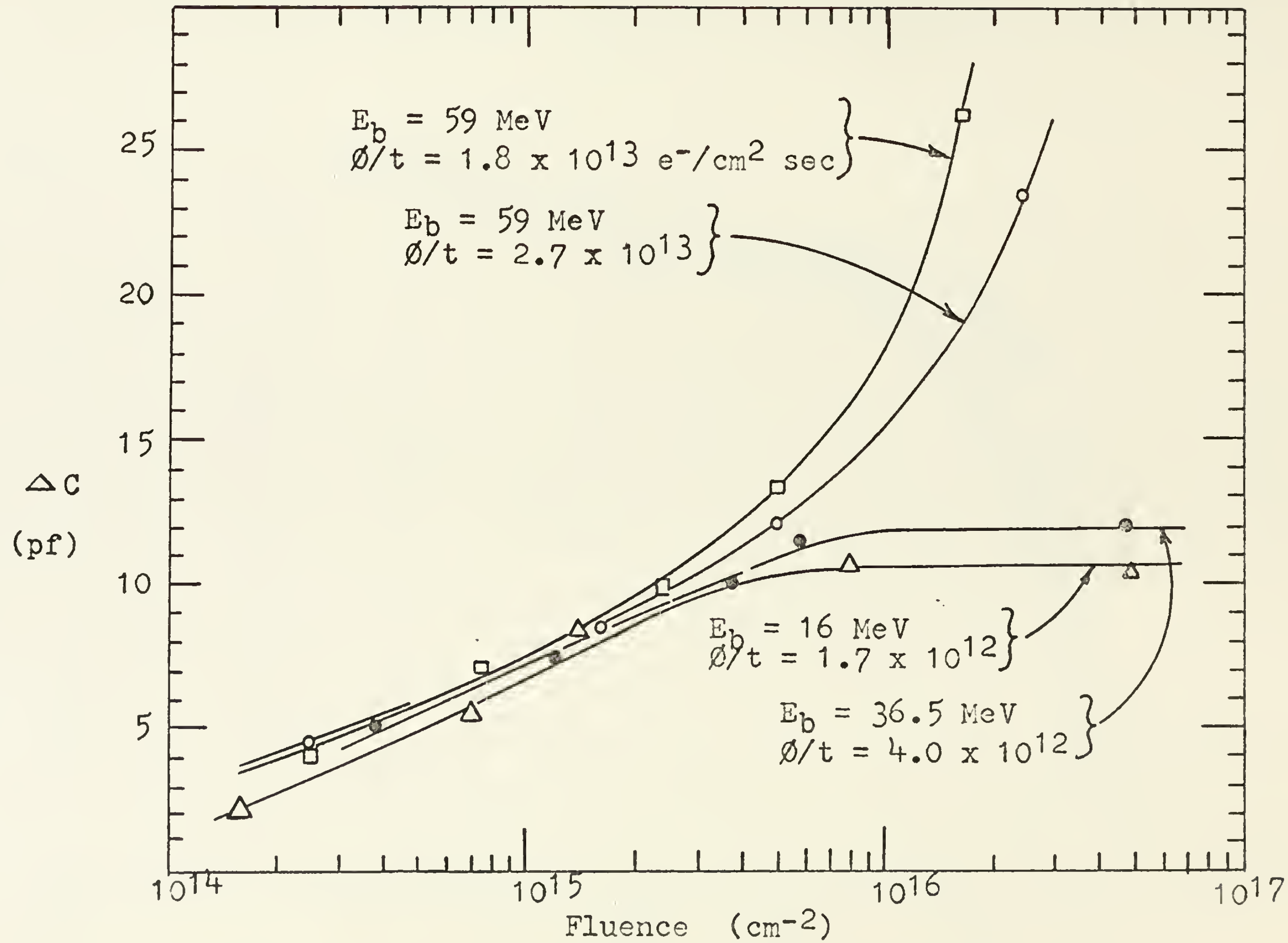


Figure 12. △C vs Fluence for 2N4360 MOSFETS

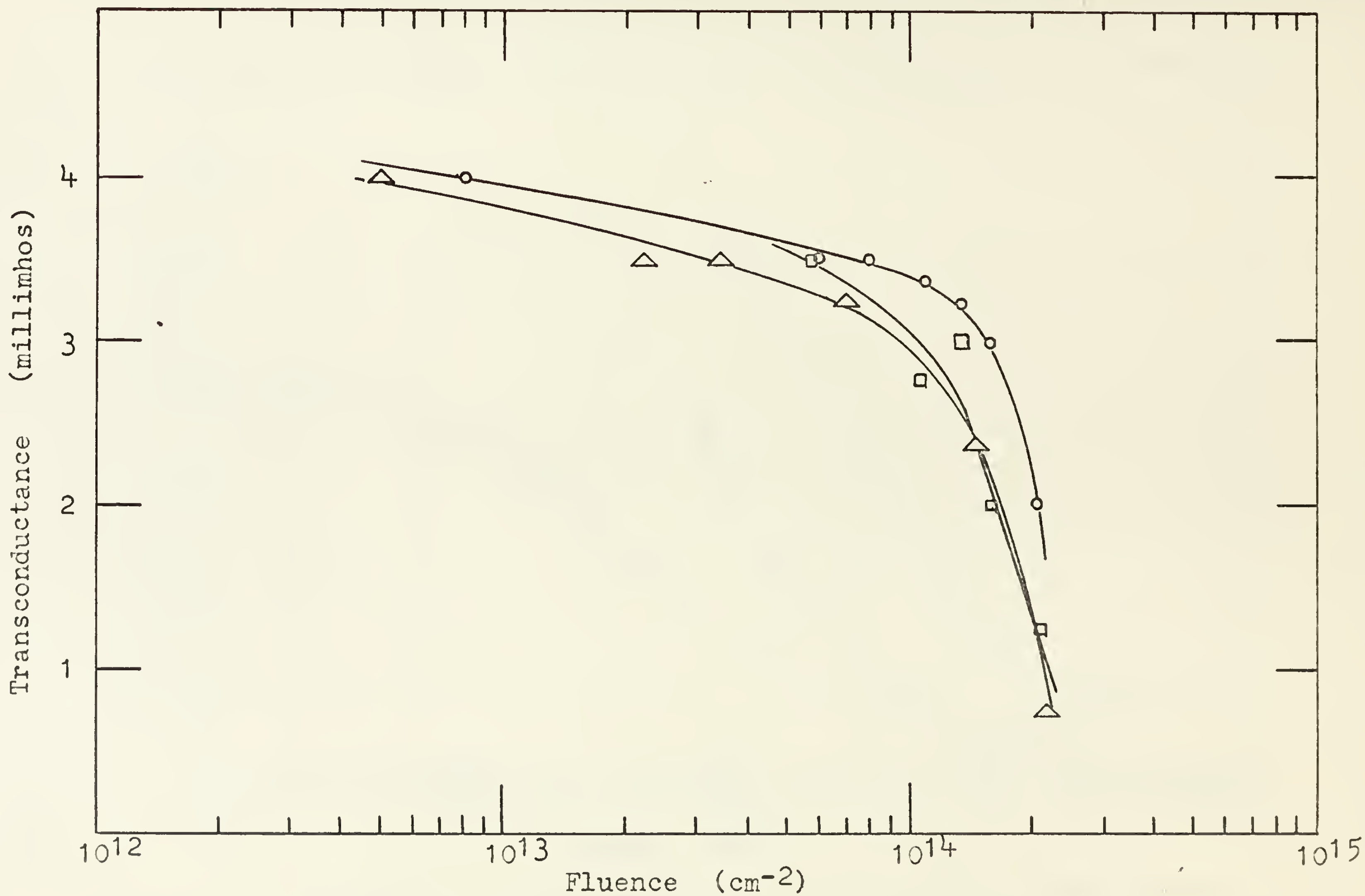


Figure 13. Transconductance vs Fluence for 2N4067 MOSFETS

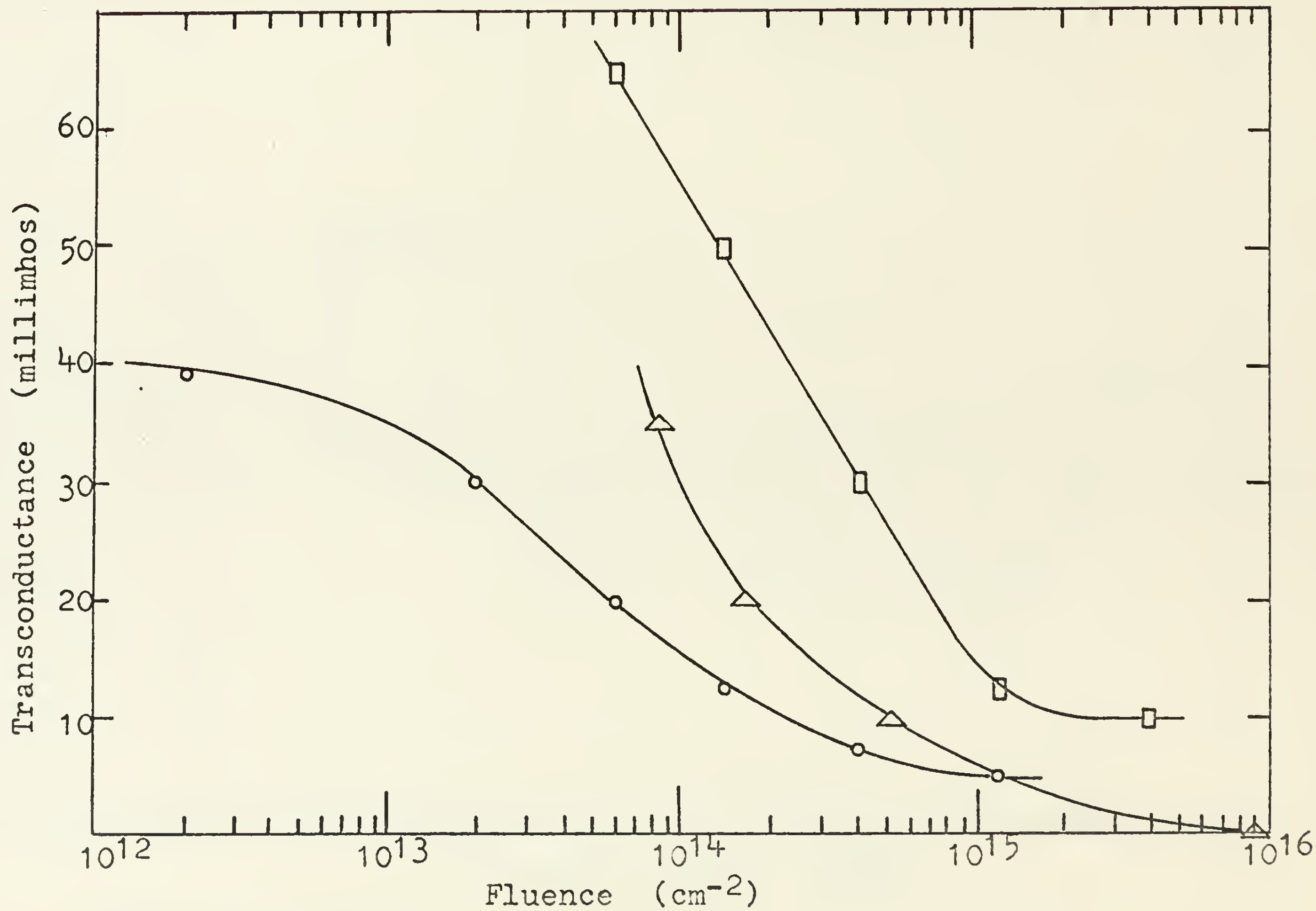


Figure 14. Transconductance vs Fluence for 2N4360 MOSFETS

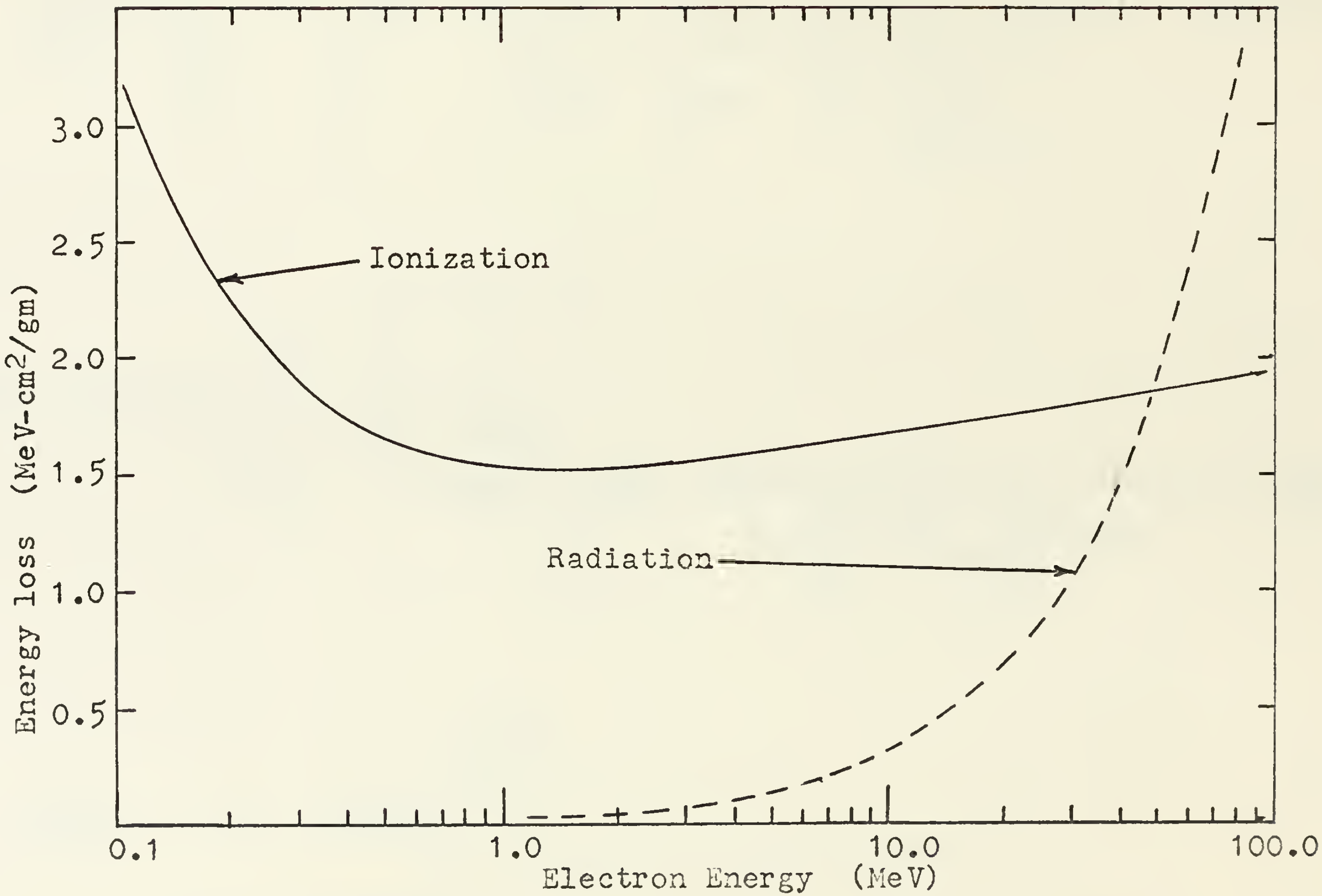


Figure 15. Energy loss vs energy for electrons in silicon

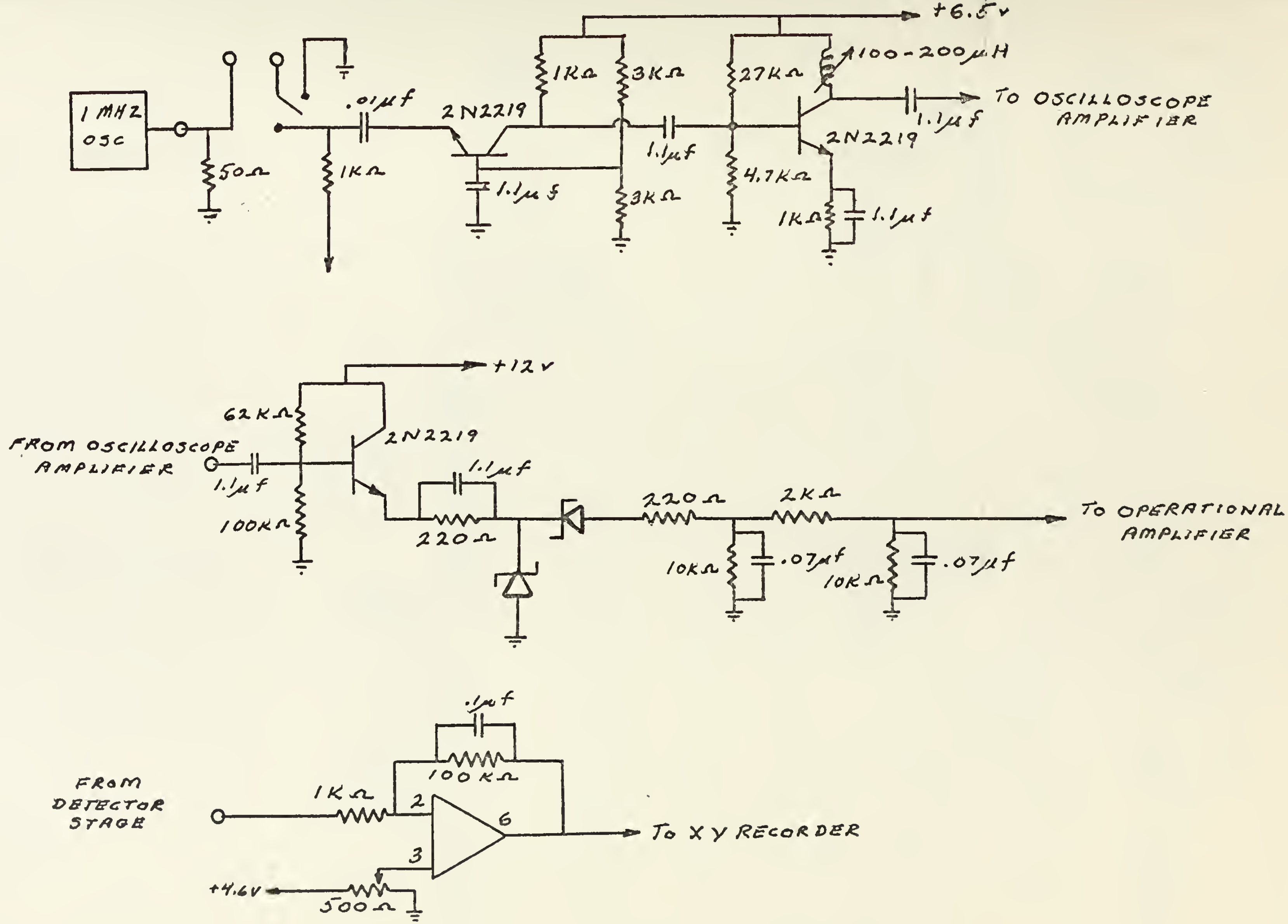
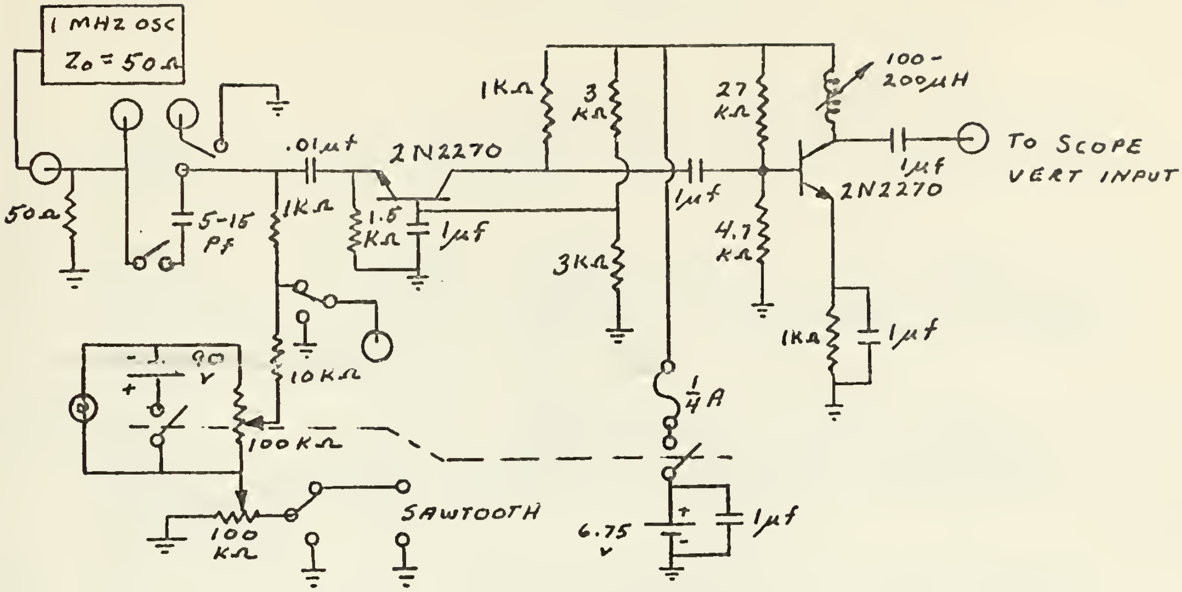


Figure 16. Capacitance measuring device as constructed



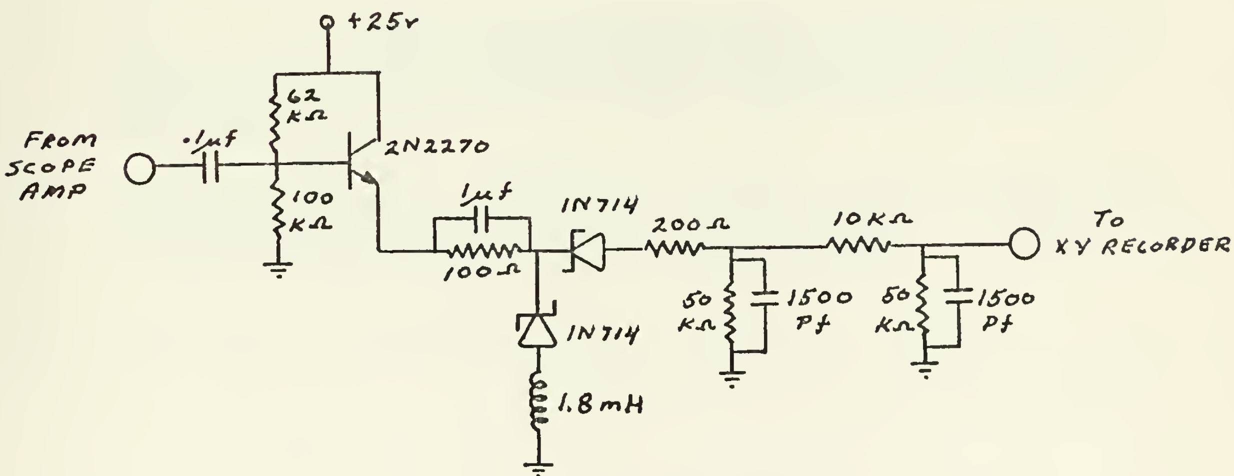


Figure 17. Capacitance measuring device

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13. ABSTRACT

This study investigates the behavior of TTL NAND Gates (Signetics SE480Q) and MOS Field Effect Transistors (2N4067) in an electron radiation environment (produced by the Naval Postgraduate School Linear Accelerator).

The electron radiation within two planetary radii of Jupiter is estimated to be of the order of 5×10^7 electrons per square centimeter per second. The "Grand Tour" outer planets space probe was to spend about ten hours in this environment thus receiving an exposure of about 2×10^{12} e^-/cm^2.

Exposures of about 10^{15} e^-/cm^2 for TTL NAND Gates and 10^{14} e^-/cm^2 for the MOSFETS were required before failure or serious degradation of performance occured. Therefore, in the electron environment near Jupiter, satisfactory operation should be expected for about 500 hours for the MOSFETS and 5000 hours for the TTL NAND Gates.

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Radiation damage						
Jupiter						
Linear Accelerator						

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